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PROPELLANT-ACTUATED DEEP WATER ANCHOR. INTERIM REPORT

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Port Hueneme, California

August 1973

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Three anchor flukes (one for rock and coral, one for sand and stiff clay, and one for soft clay) were designed to satisfy the realm of seafloor anchoring possibilities. Results of the land tests were that actual and predicted launching system performance were comparable within 9%, and the anchor launch vehicle was structurally sound. The anchor will be tested in a range of water depths and seafloor types to complete the development phase.

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A propellant-actuated deep water anchor is being developed to moor deep ocean surface and sub-surface structures. The anchor is designed to have a long-term holding capacity of 20,000 pounds and function in seafloors ranging from very soft sediments to hard rock (basalt) in water depths to 20,000 feet. The anchor has been designed, fabricated, and tested on land. Deep water use of this anchor requires that it be expendable; therefore, surplus ammunition components are used in the launching system (e.g., gun barrel, cartridge, primer), and a simplified structural shape is used for the reaction vessel.

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14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Anchors (marine)						
Mooring						
Underwater structures						
Ocean bottom						
Sediments						
Rocks						
Deep water						
Actuators						

CONTENTS

INTRODUCTION

Subject and Purpose of Report

This report describes the development by the Naval Civil Engineering Laboratory (NCEL) of a propellant-actuated direct embedment anchor (deep water anchor), and reports the results of a land testing project used to define the anchor's gun system performance. The project is sponsored by the Naval Facilities Engineering Command. The overall objective is to develop practical embedment anchors which are both reliable and efficient for use in mooring deep ocean surface or subsurface structures. The anchor is designed to be functional in water depths to 20,000 feet, to have a long-term holding capacity of 20,000 pounds, and to develop this capacity in seafloors from soft clay to hard rock.

Background

Present deep water mooring installation techniques require continuous at-sea operation through a long-time period; therefore, the installation process is subject to inclement weather. It would be advantageous if improved hardware and procedures were available to ease and speed installation. The solution to this problem, however, encompasses a broad spectrum of considerations. Anchor designs, special appurtenances, connective gear, and special operational techniques are among the more critical areas that need improvement. The single most important consideration is the anchor design because improved anchors can alleviate problems in the other areas.

Based upon the operational requirements established in the program objectives, the state-of-the-art, and the available time frame, it appeared that this critical mooring problem could be most easily solved through development of a propellant-actuated direct embedment anchor.

The direct embedment anchor best satisfies the requirements of a deep ocean anchorage. Two advantages of this type anchor are the capability to embed directly into the bottom without the necessity of dragging and the capability to resist significant uplift loads. Direct embedment shortens the lowering and placement time, enhances the precision of placement, and reduces the quantities and sizes of accessory gear. Uplift resistance provides for both reduced amounts and variety of connective gear and greater flexibility of application of the anchor. Of the direct embedment anchor types, e. g., vibratory, propellant-actuated, hydrostatic, free-fall, the propellant-actuated anchor offered

the greatest promise of being simple, reliable, and economically feasible, primarily because a major cost of the system, the gun barrel could be obtained by shortening surplus Army or Navy guns.

Approach and Scope

Development of the direct embedment anchor involved utilization of existing components and simplified structural shapes, design of a rapid keying anchor fluke to allow the most efficient use of penetration energy, and an optimization study between seafloor soil conditions, fluke behavior, and launcher system performance.

The launcher system and the safe and arm device were developed for NCEL by other Navy Laboratories. The remainder of the anchor system was designed and fabricated at NCEL.

This report provides a description of the anchor, documents the results of the land testing program used to define launcher system performance, and outlines the procedures involved in designing the anchor. Included in appendices are a soil-anchor interaction analysis to determine required sizes of flukes and an optimization study to determine the correct propellant characteristics for proper performance at any water depth to 20,000 feet.

DESCRIPTION OF EQUIPMENT

General

The deep water anchor shown being lowered into the sea (Figure 1) was conceived as an expendable hardware item. Therefore, every effort was made to use simplified structural shapes and existing components to achieve a design that could be inexpensively modified. The anchor is about seven feet high and weighs about 1,800 pounds. It consists of two major parts, a launch vehicle and a projectile which includes piston and fluke. Three different flukes are needed to satisfy the realm of anticipated seafloor conditions (sand, clay, and rock). The three-foot long sand fluke and the five-foot long clay fluke are similarly configured plate-like projectiles. A three-fin, three-foot long, arrowhead-shaped projectile will be used for rock anchoring.

Functional Description

The anchor schematically illustrated in Figure 2 is designed to be control-lowered to the seafloor and to be functional in water depths from 100 feet to 20,000 feet. Above 100 feet safety switches prevent activation. When a probe protruding 26 inches below the fluke tip contacts the seafloor, the firing sequence is initiated. The projectile (fluke/piston) is restrained from movement by the shear pin links (modified turnbuckles) until pressure within the gun barrel reaches 3,000 psi. At this point the projectile which is connected to the main

lowering line through the flaked downhaul cable is propelled into the seafloor at velocities up to 400 feet per second. After penetration is complete, a small pull on the main cable causes the fluke to key (rotate into its resistive position). After about a week the launch vehicle, which is attached to the main cable by a corrosive link, is designed to fall free thereby eliminating a potential source of abrasion to the cable.

ANCHOR DESIGN

Flukes

Two types of flukes were designed to satisfy performance goals in seafloor sediments and rock.

Sediment Flukes. To satisfy anchoring requirements in seafloor sediments, two flukes were chosen, one fluke for sand and stiff clay (sand fluke) and one for soft clay (clay fluke). The basic shape of these sediment flukes is illustrated in Figures 3 and 4 by the sand fluke. It is shown with a piston, in its penetrating position, Figure 3, and its keyed or resistive position, Figure 4. The bent-plate configuration was necessary to ensure that the fluke mass and drag area were balanced about the piston. Fluke characteristics are:

Characteristic	Sand Fluke	Clay Fluke
Length (in.)	38	63
Width (in.)	18	30
Plan Area ($ft.^2$)	4.5	12.5
Fluke Weight (lbs.)	147	337
Piston Weight (lbs.)	116	116
Piston Extension Weight (lbs.)	24	24
Connective Gear Weight (lbs.)	13	13

These flukes were designed to conform to the requirements for an optimum direct embedment anchor: they are streamlined for deep penetration, they are quick keying, and they should obtain high holding capacities.

The principal feature of the new fluke design is the technique used for keying. This quick keying feature is patterned after the free-fall anchor fluke (Smith, 1966). There is no mechanical connection between piston and fluke at their contact point. The fluke is held tight against the piston by the turnbuckles before launching as shown in Figure 2. After firing fluke-piston contact is maintained during initial penetration by the inertial force of the piston and in later stages of penetration because soil drag on the fluke exceeds that on the piston. After embedment, an upward pull on the cable attached to

the piston separates the piston from the fluke and initiates keying. The fluke was designed to provide a reasonable keying distance while maintaining structural integrity.

An optimum fluke design was attained by an empirical and theoretical analysis and some model testing. Using anticipated seafloor soil types, a trade-off study was made between fluke sizes and shapes to determine which fluke(s) could be driven into the seafloor with a minimum of energy while attaining the required long-term holding capacity of 20,000 pounds. This allowed for a small, light gun system to be chosen to embed the flukes because the required energy had been minimized. Appendix A outlines the trade-off study.

Figure 5 presents the results of a series of laboratory and small-scale field tests to evaluate keying distance as a function of keying arm length. These tests were the basis of selecting the eccentric keying distance of .3 L (L = fluke length) to cause keying in a distance equal to about 1 3/4 L measured from the fluke tip. The top of the fluke, therefore, moves less than the fluke length before keying. Full-scale at-sea tests indicated that keying actually occurs somewhat quicker than shown in Figure 5. Rapid keying ensures that the anchor, once established, will function as a "deep" anchor, an anchor whose capacity is not significantly affected by small upward movement. Taylor and Lee (1972) have given a more complete description of this phenomenon.

Rock Fluke. There is little information available to design projectiles that will penetrate rock and then resist a specified pullout load. As a result, the design of the rock projectile was accomplished using considerable engineering judgement based on the results of full-scale anchor tests of others (Smith, 1971), results of Sandia Laboratory's investigations of the penetration phenomenon (Young, 1970; Feltz, 1972), and results of model penetration tests.

A model test program (True, 1972) was performed to determine the penetration characteristics of projectiles of various shapes in simulated rock. The results provided information useful in the rock fluke design. A three-fin fluke was chosen because model tests indicated that this configuration developed, for a given amount of penetration energy, about the same holding capacity as a plate or long solid shaft of equal mass. Since penetration may not be sufficient to completely bury the fluke, a three-fin fluke is more desirable than other shapes because it affords increased moment resistance to randomly directly loads. Model test data also indicated that large fluke serrations are unnecessary; a fluke with a roughened surface is as effective.

Full-scale tests (Smith, 1971) showed that a three-fin fluke was very effective in coral and partially effective in basalt. In one basalt test the fluke cracked on impact and failed prematurely, while in another the fluke exceeded design goals in holding capacity. It was apparent from the tests that the basic configuration was satisfactory. However, a fluke with stronger and tougher steel, free of residual stresses, and free of points of stress concentration was needed.

The rock projectile, including fluke and piston, is shown in Figure 6. The piston is 26 inches long and weighs 115 pounds. The piston is not fixed to the fluke shaft; it fits over the shaft and can separate during penetration. Constructed in the chosen three-fin configuration, the fluke is about three feet long, has a two-to-one taper to the nose and weighs 160 pounds. With connective gear the total weight of the rock projectile is 300 pounds. One-inch-thick, 100 ksi yield (4140) steel is used for the plates and center shaft while 160 ksi yield (4340) steel is used for the fluke nose. The nose has a length-to-diameter ratio equal to three because this was found to be the most efficient rock penetrating shape (Young, 1970). The nose must remain intact during impact to properly fracture the rock to allow the weaker three-fin portion to penetrate without damage. Ideally the nose should have a very high yield stress and a low modulus of elasticity (Feltz 1970). Since these are opposing requirements it would have been difficult to arrive at a suitable balance between modulus of elasticity and strength without testing. Another alternative is to use high strength steel with a high modulus of toughness (Feltz, 1970); 4340 steel was chosen to satisfy these criteria. The nose-tip was blunted at 1½ inches from what would have been the tip at an included angle of 100° to eliminate tip bending or hooking during penetration.

The fluke as mentioned is about three feet long, and the point of cable attachment is about two feet above the tip of the fluke. The dimensions were partially predicted on anticipated penetration depths in basalt. Though available penetration formulas were derived from tests on uniformly-shaped penetrometers, they can be used to bound the problem. Penetration using the Poncelet equation modified by Petry (Christians, 1967) and using the Sandia empirical equation (Young, 1967) is estimated to be between two and eight feet in basalt. It appears that load will always be applied at or below the seafloor, thereby minimizing bending stresses. Another design consideration was that projectile acceleration be less than 2,000 g's to reduce stresses in the down-haul cable and connective gear. A projectile weight of 300 pounds satisfies this criterion. To maintain structural integrity, remain within the weight limitation and use the three-fin configuration, about a three-foot-long fluke was required.

Launch Vehicle

The launch vehicle, Figure 2, consists of a launching system and a reaction vessel. The reaction vessel is composed of a 2½-inch-thick plate welded to a 19-inch-long, 20-inch-diameter, steel pipe. It is attached by bolting to a bearing plate that is threaded on the breech end of the gun.

The anchor gun performance is improved by increasing the ratio of launch vehicle mass to projectile mass. A point of dimenishing returns is reached when this ratio is about three. The mass of the reaction vessel was made great enough to give a 3-to-1 ratio between the launch vehicle and the clay projectile, thereby giving an even larger ratio with the sand and rock projectiles. Trapped water further increases

the reaction mass, but the magnitude of this effect is difficult to assess. Previous embedment anchor designs (Smith, 1971; Smith et al, 1970) have relied upon trapped water to provide a large portion of the required reaction mass, but this procedure results in structural configurations that are costly and difficult to fabricate. Trapping water for a significant part of the reaction mass reduces the on-ship handling mass. However, because the anchor is a light piece of equipment to begin with, the less costly approach of using steel for the reaction mass was chosen over trapping water.

A downhaul cable 75-feet long is flaked on a board that is attached to a launch vehicle. This length of cable will account for a maximum 50 feet of penetration in soft clay and a predicted 25 feet of launch vehicle recoil at full charge.

Launching System

In design of the anchor launching system, it was decided to pursue the use of existing ammunition components wherever possible in an effort to reduce unit cost. Stockpiles of existing Army and Navy gun tubes were surveyed in light of the following anchor launcher performance requirements:

Muzzle Velocity	450 fps maximum; 200 fps minimum
Projectile Weight	500 lbs. maximum; 300 lbs. minimum
Projectile Acceleration	2000 g's maximum
Gun Barrel Length	48 inches maximum
Operable Water Depth	20,000 ft. maximum; 100 ft. minimum

Based upon these requirements, a smooth-bore tube approximately three to four feet long, with a four-inch inside diameter and usable existing breech threads was desired.

While no Navy barrels appeared to be readily adaptable to this configuration, several Army tubes approached these requirements. The 90mm, M41 tank gun tubes were most plentiful, and a design effort to utilize these tubes was undertaken. Unfortunately, the tapered chamber portion of the tube comprises most of the length useful to this application.

Energy and propellant loading density requirements indicated that a cartridge case about ten inches long could contain a sufficient quantity of single-base gun propellant to achieve desired anchor velocities. However, the chamber diameter ten inches from the breech face is still greater than the desired smooth-bore diameter. Use of a longer case would reduce this diameter while reducing remaining projectile travel. Either a longer barrel would then be necessary or the anchor assembly would have to experience higher launching accelerations to achieve the same velocity in a shorter distance.

It was decided to circumvent this problem by utilizing the ten-inch long cartridge case, smooth-boring the tube to a diameter of 4.25

inches, and employing a special polyethylene obturator to allow use of the partially tapered bore, Figure 7. Since the piston is muzzle loaded, the obturator disc must be loaded with the cartridge case. This is accomplished by fashioning the disc to serve also as the cartridge case closure plug. Pressurization of the case forces the obturator/plug against the piston base. As the piston is accelerated down the tube, the plastic flows to provide obturation over the entire firing cycle, Figure 8.

Existing components were utilized as follows:

Army 90mm M41 tube - shortened and smooth-bored
Army M108B1 Cartridge Case - shortened
Army M58 primer - shortened and reduced charge
Navy smokeless propellant (PYX)

The breech block was designed to mate to the existing breech threads on the M41 tube. A high-strength steel ring was incorporated into the base of the cartridge case to strengthen the unsupported region where the safe and arm device (S&A) is inserted into the breechblock. Explosive interface tests were conducted to mate the S&A output charge to the primer percussion element and the primer black powder charge to the main propellant charge.

An interior ballistics computer simulation was utilized in the design of the overall propulsion system. "Fine-tuning" the system is then achieved by slight variations in the charge weight and grain configurations (see Appendix B). Similar anchor velocities are desired independent of firing depth. However, external pressure can vary by more than 8000 psi over the operating range, resulting in significant effects on the gun performance. Fortunately, by designing the propulsion package to provide sufficient velocity at the shallow end of the range without generating excessive pressures at the deep end, success is virtually achieved. As shown in tabular form below, at progressively increased depths, increased outside water pressure impedes anchor motion more, resulting in higher chamber pressures, more propellant burned, and ultimately more energy transferred to the anchor.

Depth (ft)	Outside pressure (psi)	Chamber pressure (psi)	Fraction burned	Velocity (ft/sec)
0	0	22,000	0.66	330
10,000	4,400	33,000	0.89	365
20,000	8,800	45,000	1.00	385

Indeed, velocities are higher, rather than lower, at increased firing depths. If necessary, even these variations can be reduced by the use of several propulsion packages, to be used selectively for various firing depth ranges.

Firing Mechanism

The firing mechanism (components shown in Figure 2) consists of a weighted touchdown rod with a 2½-inch square base pad, a safe and arm device (S&A), and a power package with a nickel-cadmium battery supply and the appropriate electronic circuity to sequentially energize two solenoid valves within the safe and arm device.

The touchdown rod slides freely when frontal force equalling the resistance supplied by ¼ psi shear strength soil acts upon it. The force required to cause a bearing capacity type failure in ¼ psi soil is equivalent to a water-drag force on the rod occurring at 17 ft/sec, which is considerably greater than the lowering velocity, 2 ft/sec, thus providing a satisfactory margin of safety.

The S&A, Figure 9, consists of a cartridge of high pressure (1100 psi) nitrogen (N-2), an inflator, a 1200 psi volt two-way normally closed solenoid valve, a 750 psi 24 volt three-way normally vented to S&A chamber solenoid valve, a 440 psi ±10% gold shear disk, a firing pin piston/cylinder, a MK43 Mod 1 detonator mounted in a spring return out-of-line plunger, a lead cup, and a lead block. These are all contained in an aluminum housing. To minimize cost and ensure high reliability, the shear disk, firing pin, detonator, and plunger arrangement used is a proven system from the SUS (Signal Underwater Sound) MK59 series of which several hundred thousand units were manufactured and used with very good safety and detonation records.

As the anchor is lowered, hydrostatic pressure arms both the electronic package and the S&A. The electronic package is armed by a pressure switch, and the S&A is armed by the spring-loaded arming plunger moving into the in-line position. Firing will occur upon touchdown in water depths of 100 feet or more. The electronic package and the S&A remain in this armed condition until touchdown or until being recalled above the arming depth, in which case they both would disarm automatically.

When the anchor touches the seafloor, a magnet located atop the touchdown rod moves in closase proximity to the fluke-mounted magnetic switch, momentarily closing it. The power package activates the three-way valve completing the gas flow path to the shear disk. The power package delays 30 msec to ensure that the three-way valve has time to change state, then it activates the two-way valve. The gas passes through both valves and the pressure above the shear disk increases until it ruptures at 400 psi. After rupture the pressure acts on the top of the firing pin pushing it down like a piston until it strikes the detonator. This sets off the detonator which in turn sets off the lead cup (CH-6 and explosive) lead block high order (CH-6) (Figure 9). The shock wave set up by the high order detonation travels across the gap between the end of the CH-6 column and cartridge to fire the cartridge's primer.

TEST PROGRAM AND PROCEDURES

The anchor was tested to verify the designs of the hydrostatic seals, the launch vehicle, and the propellant charge. In addition, electrical and gas systems were checked at extremely low temperatures to ensure proper functioning at extreme ocean depths. The seals were checked by testing in a pressure vessel and the launch vehicle and propellant by conducting on-land firings of the anchor at the Pacific Missile Range.

The gun tube, safe/arm device, and power pack are all water-tight containers designed to maintain their structural and water seal integrity to a water depth of 20,000 feet. The safe/arm device and the power pack were tested independently to a simulated ocean depth of 20,000 feet, while the gun tube was tested with the safe/arm device to a simulated water depth of only 11,000 feet because of pressure vessel restrictions. In all these tests the procedure was to build the pressure up to its maximum value, hold it for a few minutes, and then gradually release the pressure. The various apparatii were then disassembled and inspected for structural deformation and signs of water leaks.

The propellant system is designed to give the anchor projectile (fluke and piston) a velocity of 300 to 440 feet per second. To achieve these velocities with a short gun barrel, very high acceleration is required. Consequently, both the launch vehicle and the projectile experience extreme stress conditions from inertial forces during firing. By conducting test firings with the anchor on land it was possible to examine both the ballistic performance of the gun system and the structural integrity of the launch vehicle. It was not feasible to use the actual projectile during land testing, therefore, a mass of steel was substituted for the projectile. The anchor was assembled and hung with a fluke-down vertical orientation from the wood crossbeam of a large "sawhorse-like" frame. The anchor was then loaded, armed, and fired. In all, seven tests were performed with charge weights ranging from 2.25 pounds to 3.50 pounds. Various instrumentation was used for the tests including high speed movies, videotape, electronic pressure transducer, electronic accelerometers, and mechanical pressure-reading devices. The type of data recorded for each test is summarized in Table No. 1.

TEST RESULTS

In all cases the hydrostatic pressure testing caused no structural deformation, and no leakage occurred. Testing of electrical and gaseous systems at the near-freezing temperature to be encountered at extreme ocean depths verified component functioning at this extreme.

Land-testing involved reassembling the anchor after each test. The anchor was assembled without difficulty. A procedure where the anchor was held vertical and a procedure where it was laid horizontal

were used. The horizontal assembling seemed easier. About one-half hour was required to assemble the anchor when the unit was partially preassembled. One hour was required when all components were disassembled.

Land testing provided a severe test of the structural design of the launch vehicle. Upon firing the launch vehicle reacted upwards, breaking the wood cross-beam and rising to a height of up to 90 feet. Reaction height was dependent on the charge weight. Accelerations during land firing are nearly equal to those expected in water; however, impact of the launch vehicle with the ground after firing exceeds what the launch vehicle has to withstand in water since the reaction height in air exceeds that in water and hydrodynamic drag greatly reduces impact velocity. No failures of major structural components occurred, and in general the ruggedness of the design was confirmed. Two problems were noted. The shear pin links were slammed up-and-out and against the launch vehicle body by the blow-down of the gases in the gun barrel after the piston exited. Each test caused an additional amount of bending of the bars on the launch vehicle that the links were attached to, but after six tests, little difficulty was found in using the links for the seventh test. No effort was made to straighten the links between tests. At least one bolt used to hold the cover body to the bearing plate on the gun barrel was broken during every test when the launch vehicle hit the ground. The launch vehicle usually hit the ground with its axis oriented horizontally. Consequently, the gun barrel was cantilevered from the top plate of the cover body at impact with only four 5/8-inch bolts to restrain it. The bolts were not designed for this situation. The bolts were easily replaced between tests. Both of these problems occurred during land testing; neither was serious, and both will be alleviated in water. Neither affects anchor performance.

Ballistic performance for charge weights from 2.25 pounds to 3.50 pounds was in satisfactory agreement with predicted performance. Test results are summarized in Table No. 2. The data have been given subscripts to indicate whether the data came from videotape (V), high speed movies (M), electronic accelerometer (A), electronic pressure gage (P), or copper crush gage (C). Another subscript indicates whether the quantity is a direct measurement (D) or an indirect measure (ID). Electronic instrumentation data were difficult to gather because of "ringing" as the piston slid out of the gun barrel and because of high stresses on the transducers and cables during acceleration. This was in spite of considerable effort made in transducer selection and layout to avoid these problems. As a result, after the fourth test electronic instrumentation was not used, and copper crush gages were substituted to measure peak pressure. High speed movies provided a direct means to determine the time span of a firing and the displacement-time curve for the projectile movement relative to the launch vehicle. Differentiating this displacement-time curve once gave a velocity-time curve, and differentiating again gave an acceleration-time

curve. The velocity data derived this way are reasonably accurate, but the acceleration data are suitable only as a rough check of acceleration data from other sources.

Comparisons of ballistics data to predicted values are presented in Figures 10 and 11. Figure 10 shows the final velocity of the projectile relative to the launch vehicle for different charge weights. All final velocities were derived from high speed movie data by differentiating the displacement-time curves. These data show that derived values of final velocity were in very close agreement with predicted values; not deviating by more than five percent. Figure 11 shows the peak gun barrel pressure versus charge weight. Predicted peak pressures are compared to data measured directly with either an electronic pressure transducer or a copper crush gage. Measured values did not vary from predicted values by more than nine percent.

Update

The first at-sea tests of the anchor were recently completed at the NCEL shallow water test site in 110 feet of water. The anchor was fired twice using the sand fluke and reduced charges of 2.75 and 3.25 pounds. Short-term holding capacities developed with the fluke were 42,000 pounds with 9½ feet of penetration and 48,000 pounds with about 13 feet of penetration. Reduced charges (maximum is 3.75 pounds) were used to ensure that the flukes could be recovered before the breaking strength of the cable (60,000 pounds) was reached. Even with this approach, care had to be taken to gradually increase the load to minimize the effects of ship heave. Suction beneath the fluke could have caused the load to exceed 60,000 pounds before pullout.

These results were encouraging because the soil conditions at the test site were among the most difficult that will be encountered in the deep sea. The sediment profile/consist of two to three feet of dense sand and then sandy silt. The sand attenuates projectile energy and, therefore, reduced the penetration and hence the holding capacity to be expected in a uniform silt deposit. The anchor will continue to be tested in various water depths and seafloors.

EVALUATION OF PERFORMANCE

The land testing demonstrated that the structural design of the launch vehicle is sound. The main components and connections resisted acceleration-induced forces without suffering structural deformation or failure. Attaching the launch vehicle components to the gun barrel was accomplished easily with the gun barrel standing vertically on its muzzle end. Assembling the anchor proved to be a relatively simple process requiring about one hour when all components were initially disassembled. About one-half hour was required when the launch vehicle was left assembled from a previous firing. Assembling the fluke to the launch vehicle with the launch vehicle laying down seems to be the most

satisfactory arrangement. The bolts used to attach the launch vehicle cover to the bearing plate detracted from the otherwise simple design, and the bolts failed repeatedly when the launch vehicle impacted the ground after firing. In future launch vehicles the bearing plate should be eliminated and the top plate of the cover made to screw directly onto the breech end of the gun barrel. This would reduce machining costs and further simplify assembly of the anchor. The bending experienced by the bars on the launch vehicle that the shear links attach to can be easily eliminated by doubling the size of the bars and eliminating the bosses put on the existing bars. This does not require any modification of the shear links.

All the hydrostatic seals on the anchor appear to be satisfactory as demonstrated by pressure vessel testing. No modifications appear to be required. Regular maintenance of all O-ring surfaces is critical. Unlike most ocean hardware whose seals are broken only in a dry laboratory, many of the seals of the deep water anchor are broken when the anchor is fired. Consequently, both sides of the seal are exposed to the corrosive effects of seawater. Fresh-water washing and lubricating of all O-ring surfaces should be done soon after the equipment is recovered from the ocean. Although the anchor was originally designed to be expendable, it appears that the launch vehicle could be retrieved and used repeatedly in shallow-water (100 to 500 feet) anchorages.

The ballistic performance of the launching system was very satisfactory. The computer model provided by the Naval Ordnance Station was in good agreement with data measured in the field on land. This agreement has eliminated the need for measuring ballistic performance during underwater firing. However, because performance changes with changes in external pressure and environmental temperature, copper crush gages will be used to the greatest extent possible to measure peak gun barrel pressure during ocean testing of the anchor. These measurements will also be important when the anchor is fired with the clay fluke as no data have been gathered with this heavier fluke.

CONCLUSIONS

Use of existing Army and Navy ammunition components such as the gun barrel, primer, propellant, and cartridge case, in the launching system of the deep water anchor is feasible. This markedly decreases system cost, allows expendability and, therefore, deep ocean usage. A new quick-keying anchor fluke has been designed and appears to conform to the requirements for an optimum direct embedment anchor fluke: it is streamlined for good penetration, quick keying, and should attain high holding capacity. Further conclusions drawn from the test programs are:

1. The launch vehicle design is structurally adequate but can be simplified by making the bearing plate an integral part of the cover.
2. The anchor is easy to assemble and assembly can be made easier by complying with No. 1, above.

3. The launching system is satisfactorily sealed against water intrusion.

4. The ballistic performance is satisfactory and is modeled well by an available computer program.

Conclusions drawn from the first sea tests were:

1. The system is workable.
2. Acceptable holding capacities can be realized in a silt seafloor.
3. The system is quickly and easily assembled and handled.
4. The new fluke design keys quickly and showed no distress either from penetration or pullout.

FUTURE PLANS

The anchor will continue to be tested in a variety of seafloors from soft clay to rock and in different water depths to 10,000 feet. As part of the program to generate performance and reliability data, the anchor will also be used where practicable in conjunction with on-going programs. In FY74 final drawings will be prepared for the anchorage system and the propulsion package and safing and arming system will be subjected to standard safety test programs. It is planned that the anchor be ready for operational use by the end of FY74. Total cost for an entire anchor system is estimated to be $3,500. Anchor deployments in water depths less than 500 feet, where the launch vehicle is retrievable, reduces the cost to about $1,200 per anchor.

To ease and speed deep sea mooring installation, techniques for auto-mooring the anchor are being evaluated. An auto-mooring system will be designed and fabricated in FY74.

ACKNOWLEDGEMENTS

The anchor launching system was designed at the Naval Ordnance Station, Indian Head, Maryland; particular appreciation is given to Al Horst of the Gun System Engineering Branch. The Safe and Arm device was developed at the Naval Underwater Systems Center, Newport, by Dave Ramstead and Dave Pimental. Phil Babineau devised equipment and techniques for simplifying the operation and handling of the anchor.

Table I. Summary of Types of Instrumentation Used For Each On-Land Firing

Test No.	Charge Weight (lbs)	Instrumentation				
		Visual Recordings		Electronic Instrumentation		Mechanical
		Video Tape	High Speed Movies	Acceler-om	Pressure Transducer	Copper Crush Gages
1	2.25	X	X		X	
2	2.75	X	X	X	X	
3	3.25	X		X		
4	3.25	X	X			
5	3.00					X
6	3.25	X	X			X
7	3.50	X	X			X

Table II. Summary of Ballistic Data With Subscripts to Indicate Source* and Whether Data are From Direct (D) or Indirect (ID) Measurements

Test No.	Charge Weight (lbs)	Launch Vehicle Reaction Height (ft)	Time to Exit (msec)	Peak Velocity, Projectile Relative to Launch Vehicle (feet/sec^2)	Peak Acceleration, Projectile Relative to Launch Vehicle (feet/sec^2)	Peak Pressure
1	2.25	$41_{V,ID}$	$25.5_{M,D}$	$295_{M,ID}$	$895_{M,ID}$	$13{,}400_{P,D}$
					$800_{P,ID}$	
2	2.75	$58_{V,ID}$	$19.0_{M,D}$	$358_{M,ID}$	$1190_{M,ID}$	$18{,}700_{P,D}$
			$19.0_{A,ID}$		$1120_{P,ID}$	
					$1100_{A,ID}$	
3	3.25	$84_{V,ID}$	----	----	$1765_{A,ID}$	$30{,}100_{A,ID}$
4	3.25	$84_{V,ID}$	----	----	----	----
5	3.00	----	----	----	$1290_{C,ID}$	$21{,}400_{C,D}$
						$22{,}200_{C,D}$
6	3.25	$83_{V,ID}$	$18.2_{M,D}$	$415_{M,ID}$	$1680_{M,ID}$	$27{,}100_{C,D}$
					$1580_{C,ID}$	$26{,}800_{C,D}$
7	3.50	$91_{V,ID}$	$14.6_{M,D}$	$430_{M,ID}$	$2020_{M,ID}$	$27{,}900_{C,D}$
					$1680_{C,ID}$	$29{,}500_{C,D}$

* V - Video Tape
M - High Speed Movie
A - Accelerometer
P - Pressure Transducer
C - Copper Crush Gage

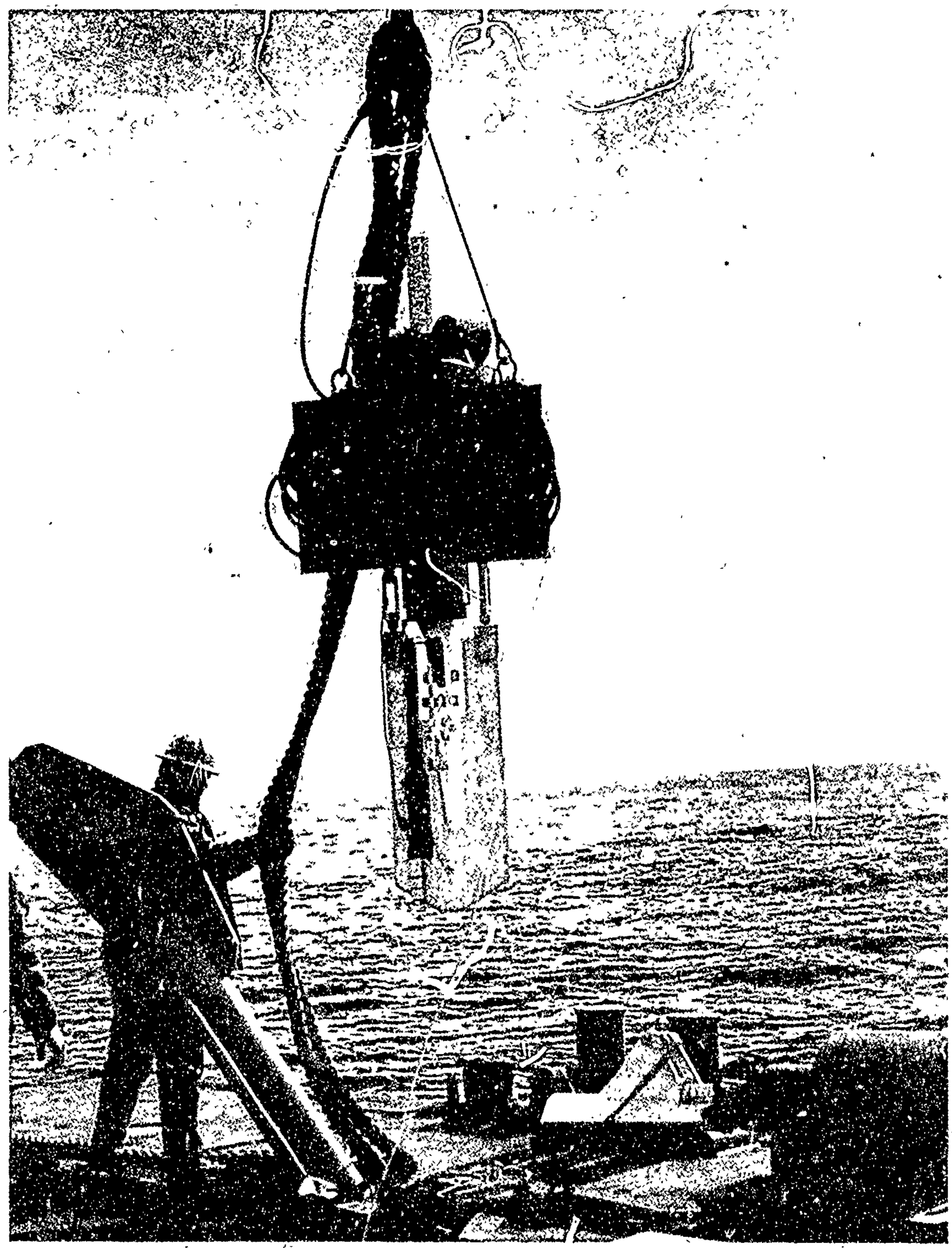

Figure 1. Propellant-actuated deep water anchor shown being lowered for its first at-sea test.

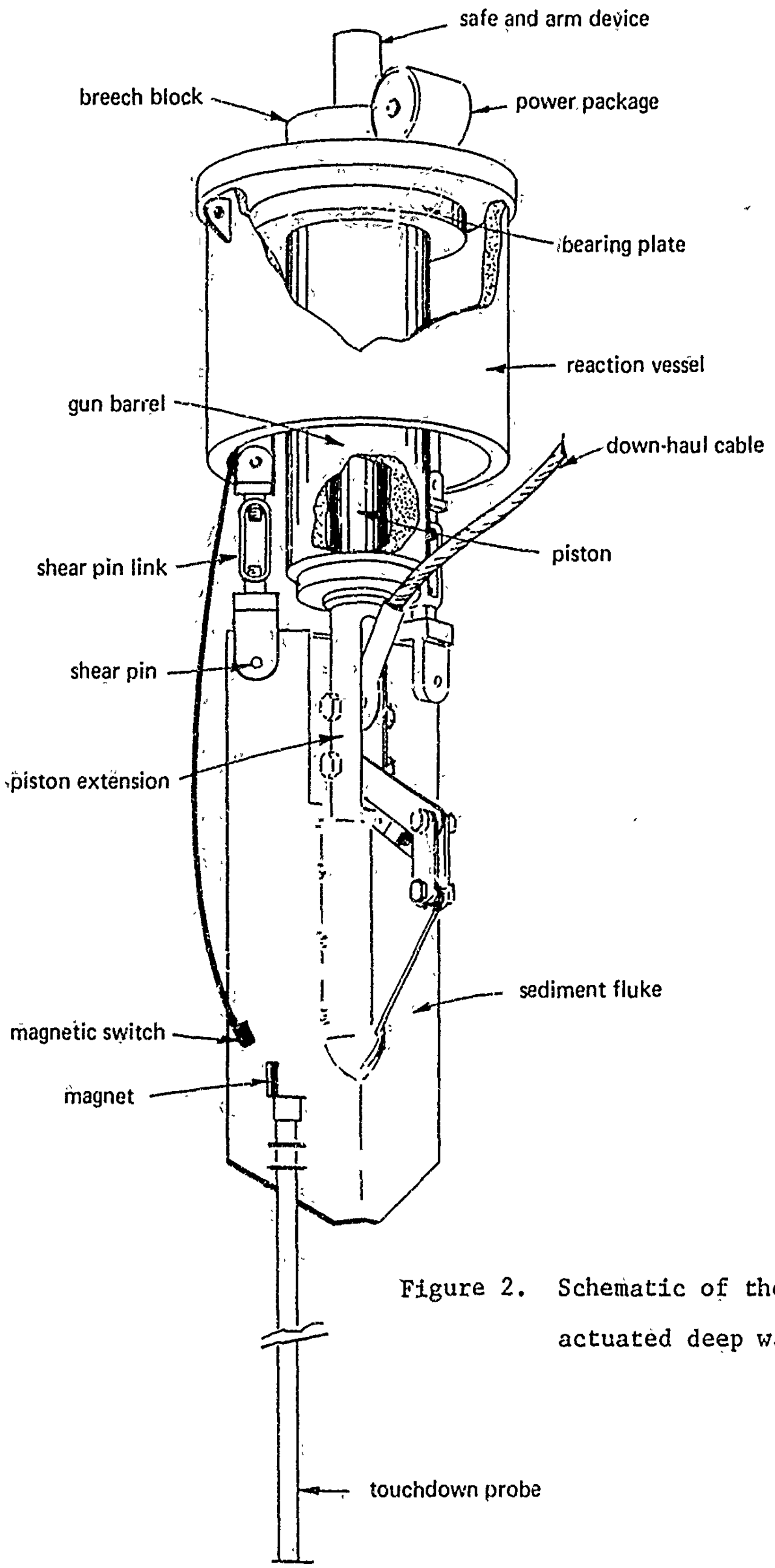

Figure 2. Schematic of the propellant-actuated deep water anchor.

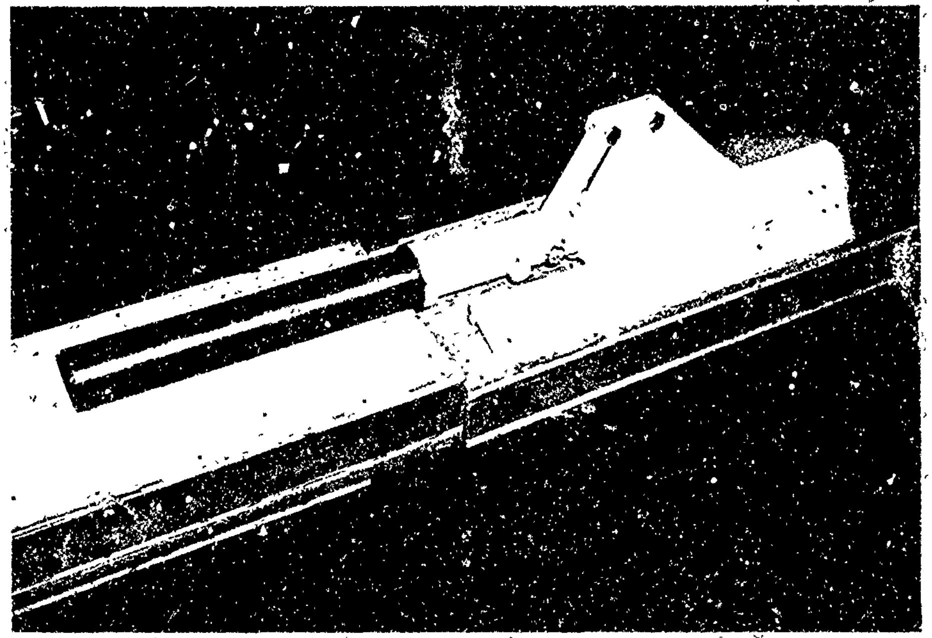

Figure 3. Deep water anchor sand fluke and piston in penetrating position.

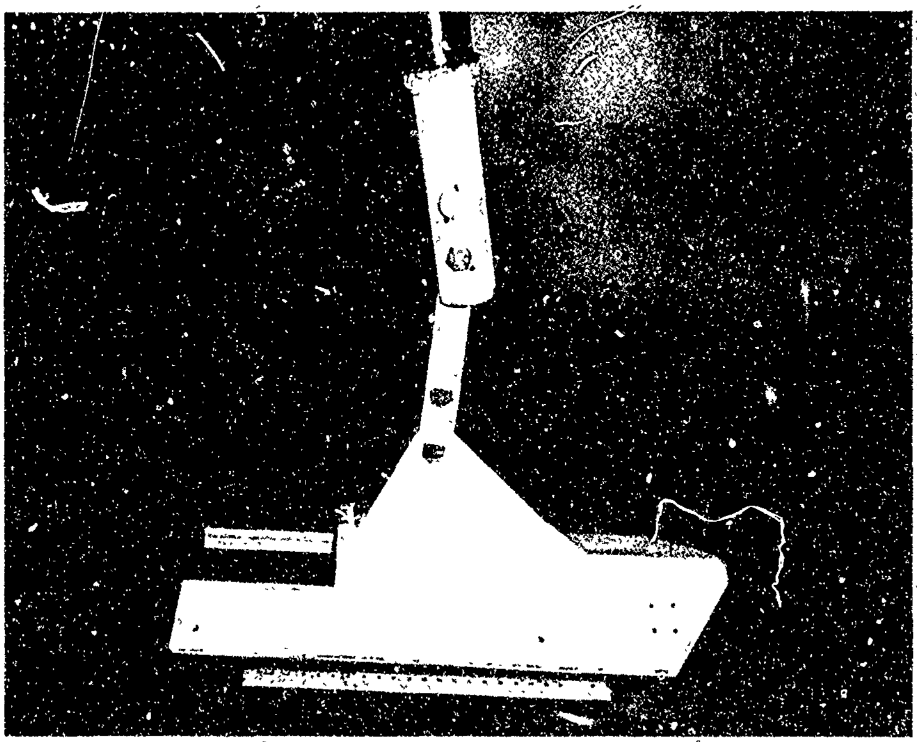

Figure 4. Deep water anchor sand fluke and piston in "keyed" position.

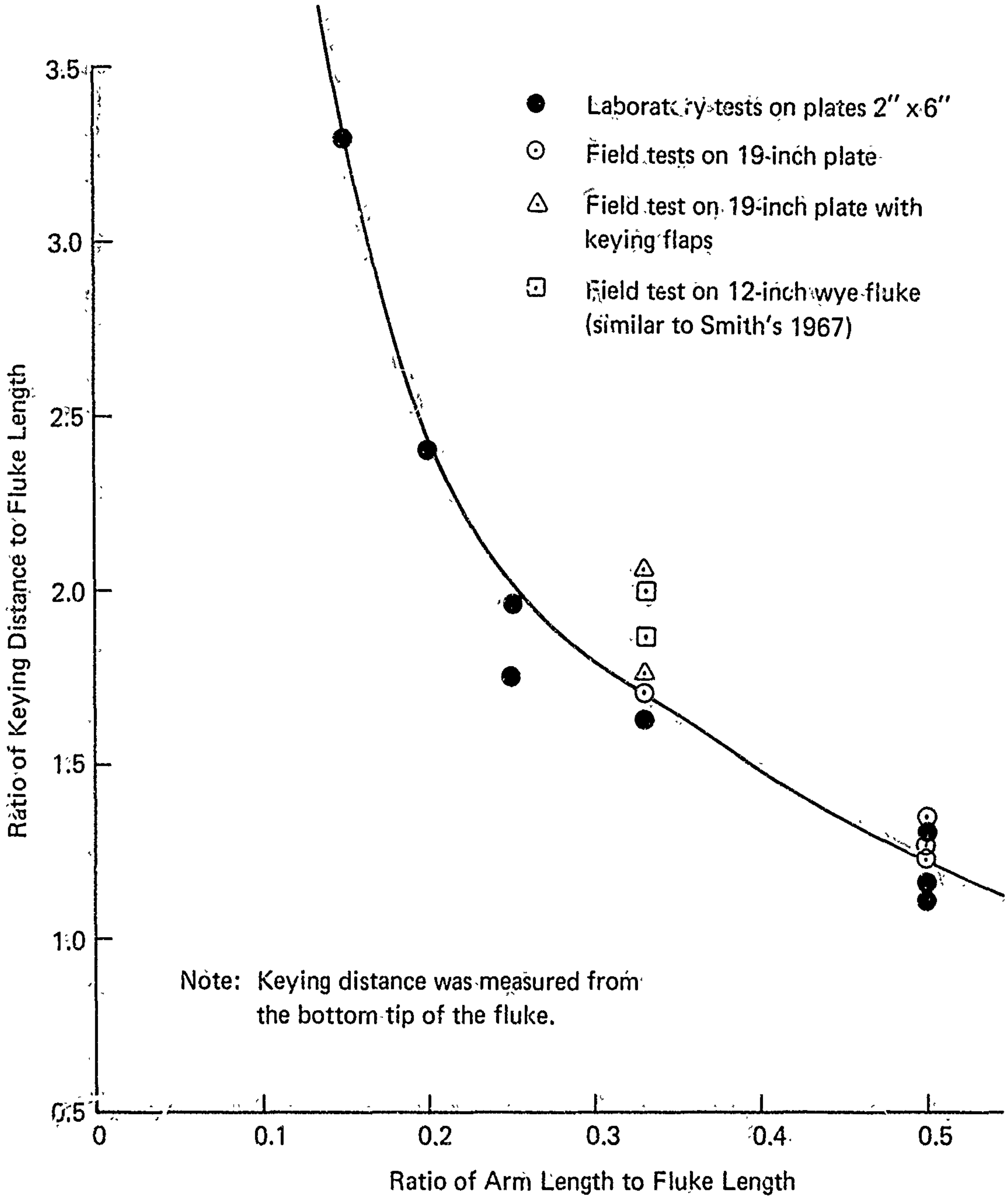

Figure 5. Non-dimensional plot of fluke length versus keying distance in sand.

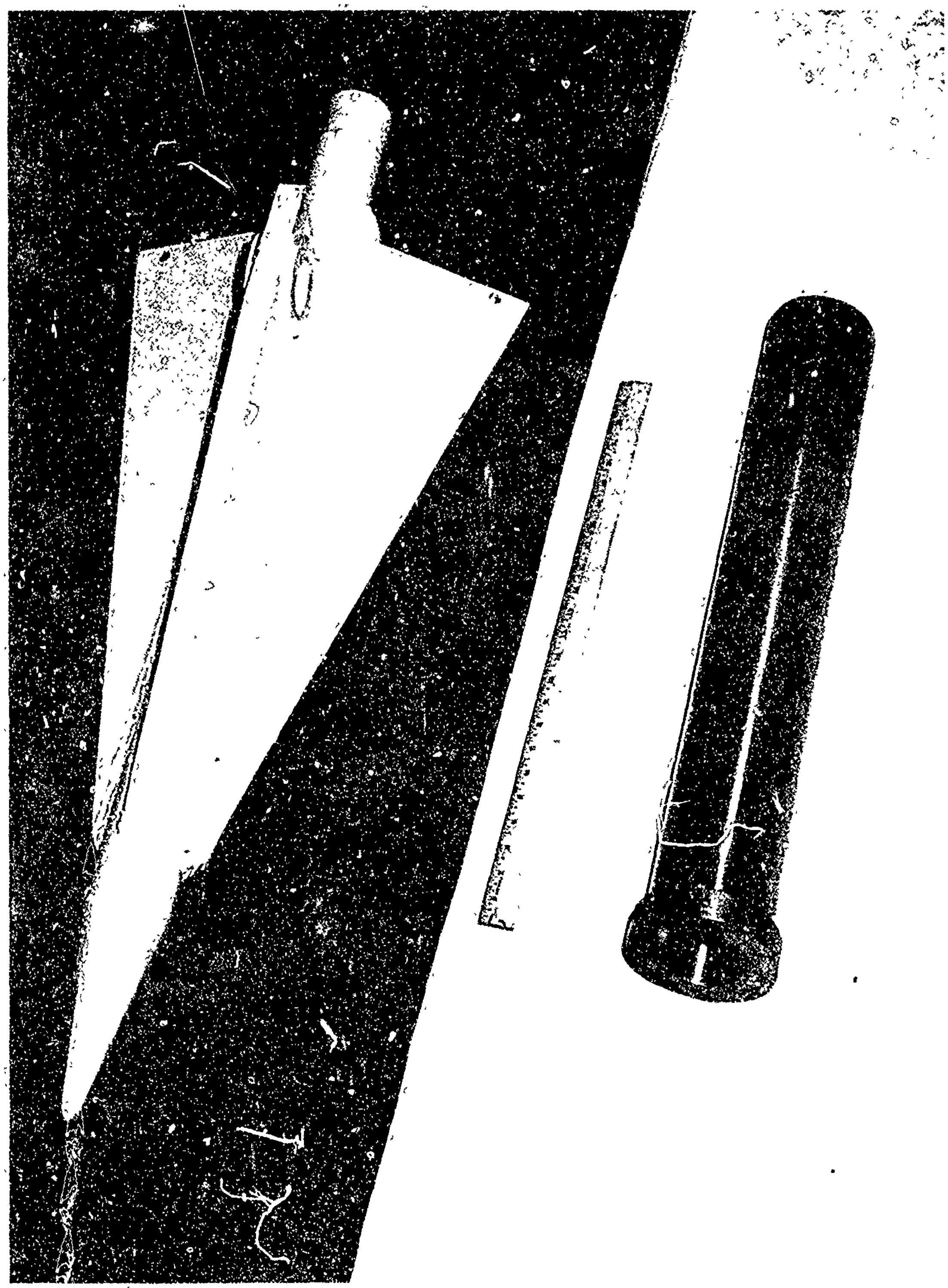

Figure 6. Deep water anchor rock fluke and piston.

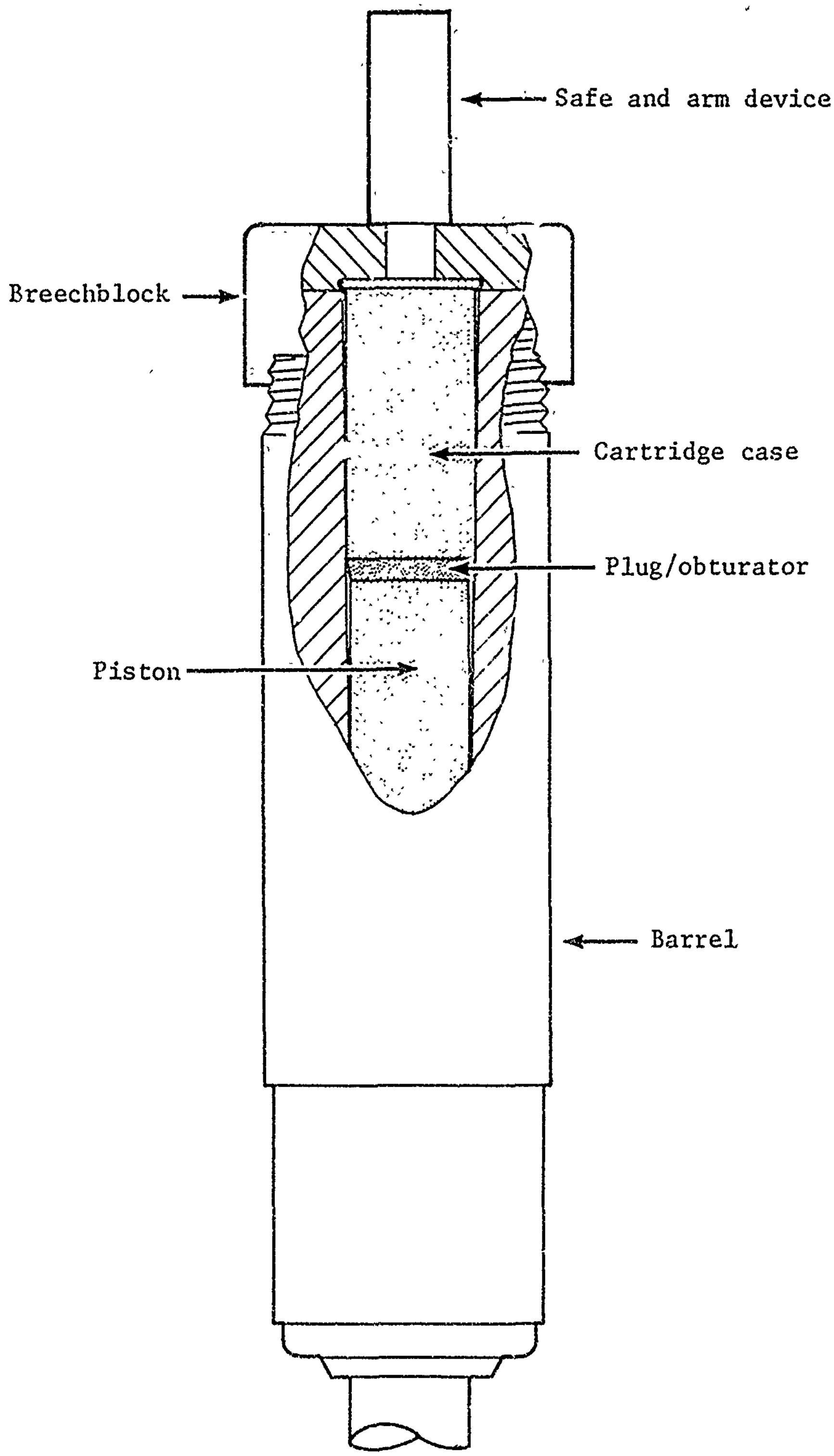

Figure 7. Deep water anchor propulsion system.

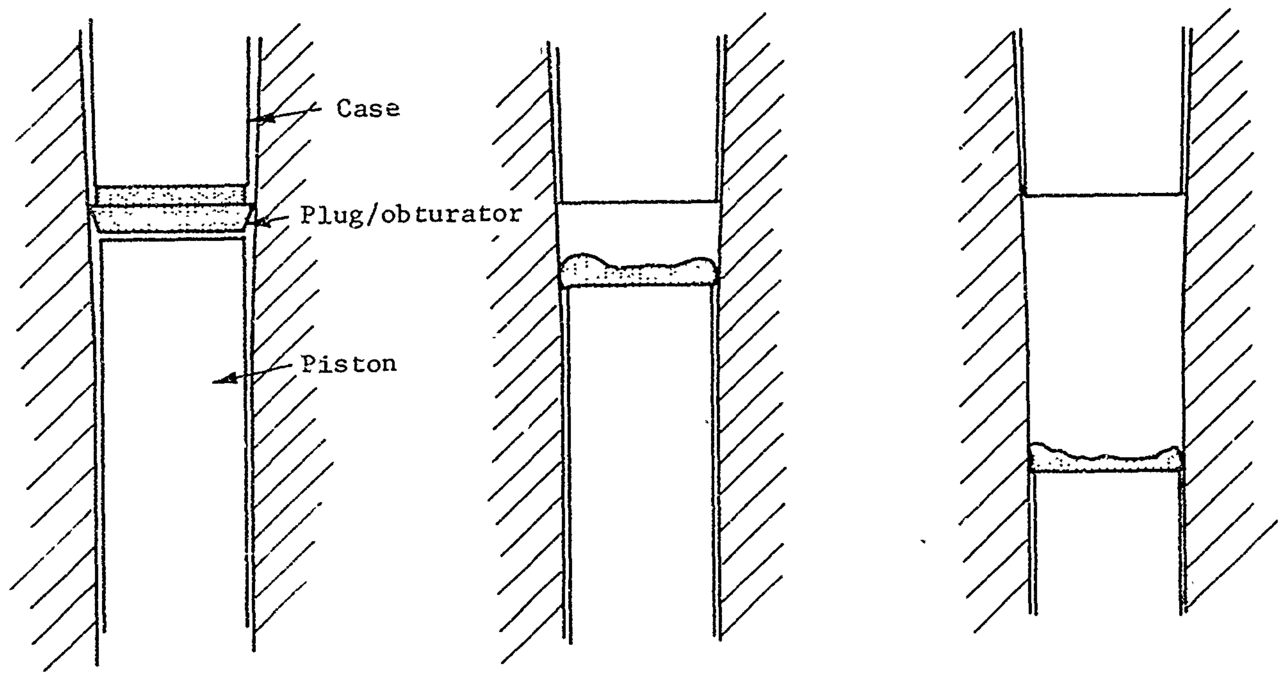

Figure 8. Obturation cycle for deep water anchor gun.

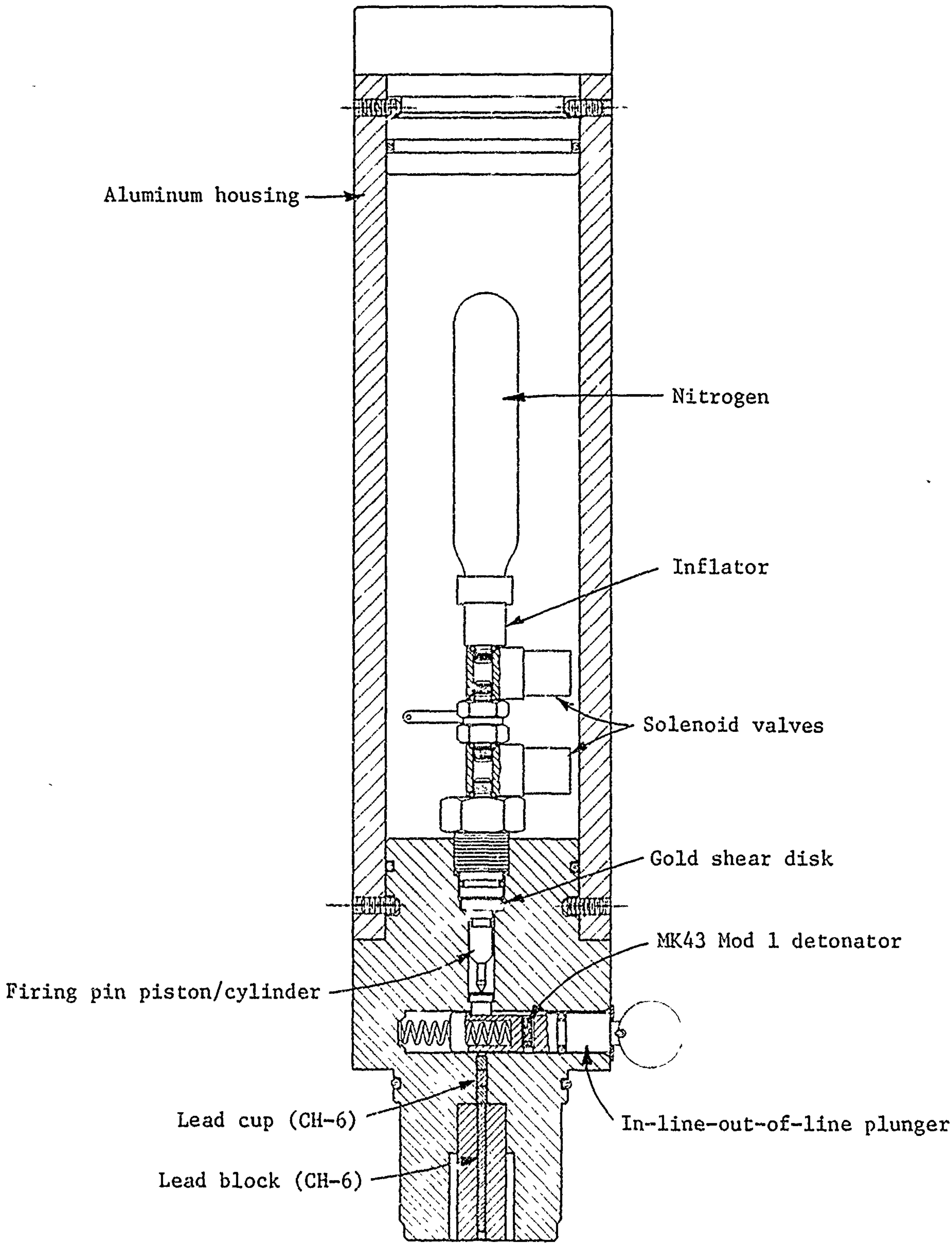

Figure 9. Schematic of the safe and arm device.

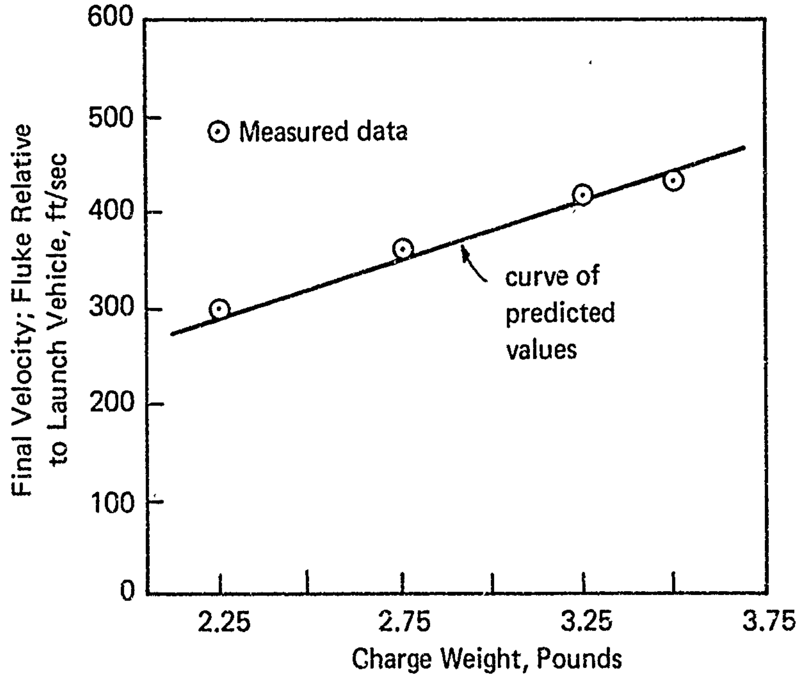

Figure 10. Final fluke velocity relative to the launch vehicle versus charge weight.

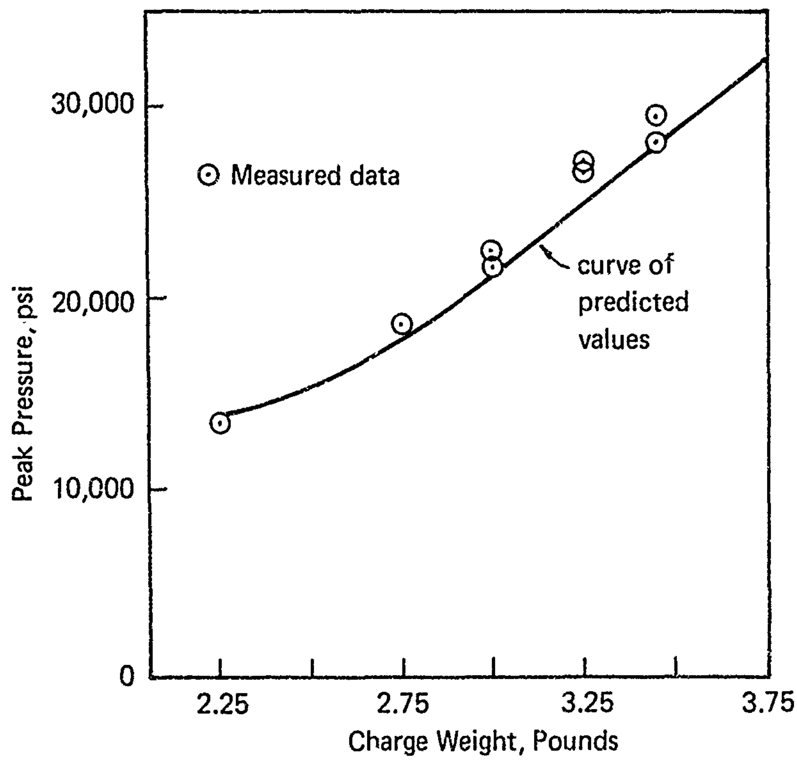

Figure 11. Peak gun barrel pressure versus charge weight.

Appendix A
SOIL-ANCHOR INTERACTION STUDY TO DETERMINE REQUIRED SIZES OF ANCHOR FLUKES

The deep water anchor was designed by first selecting the fluke(s) that would satisfy the criterion of 20,000 pounds long-term holding capacity in any seafloor. Second, the gun system capable of developing the energy to propel the fluke(s) into the seafloor was chosen. This appendix outlines the procedures used to optimize fluke design in sediments. The state-of-the-art does not permit this level of analysis for rock.

The step-by-step approach that was used to determine the required fluke(s) is as follows:

1. Establish Soil Types. Five soil types cover the realm of anticipated seafloor soils; they are listed in tabular form below.

	Soil Type	Soil Properties
I.	Medium density, non-plastic silt	γ_b = 40 pcf; $\phi = 30^o$
II.	Medium density silty sand	γ_b = 50 pcf; $\phi = 35^o$
III.	Dense sand	γ_b = 70 pcf; $\phi = 40^o$
IV.	Deep water clayey silt	γ_b = 26 pcf; $\frac{\text{shear strength}}{\text{effective pressure}}$, $\frac{c}{\bar{p}} = .3$
V.	Carbonate bonded silty clay	γ_b = 30 pcf; c = 300 psf + $1.3\bar{p}$

2. Develop Curves of Holding Capacity Versus Embedment Depth. Curves of holding capacity versus depth were plotted for each soil type using fluke widths from B = 1 to 5 feet, and ratios of fluke length, L, to fluke width, B, of L/B = 1, 1.5, and 2. Techniques used to develop these curves can be found in Taylor and Lee, 1972. A typical curve at L/B = 1.5 for type IV soil is shown in Figure A-1. Holding capacities below a ratio of depth of embedment to fluke width (D/B) equal to 2 were not calculated. It would not be good construction practice to establish such shallow anchors.

3. Limit Fluke Sizes and Shapes for Further Analysis. Curves of fluke width versus fluke embedment depth before keying (depth to fluke tip) can be analyzed to eliminate many fluke sizes and shapes from further consideration. Required data were obtained by taking depths for each fluke width from holding capacity-depth curves at a short-term holding capacity of 30 kips, and increasing the depths by values equal to fluke keying distance, assumed equal to 1 3/4 times fluke length, L. The short-term capacity of 30 kips is assumed equivalent to a long-term holding capacity of 20 kips (design requirement) to account for the possible effects of creep or repetitive loading. These curves were separated according to L/B, illustrated in Figure A-2, and soil type. A qualitative evaluation of this type curve enabled a choice of flukes

for the penetration analysis to be made. It became apparent that a point of diminishing returns was reached for each soil type for each L/B ratio. This occurs because as fluke length increases, so does fluke keying distance. Flukes eventually become less efficient with size. Flukes that would receive further analysis for soil I, II, III were 1.5, 1.75, and 2 feet wide; flukes for soil IV, the soft clayey silt, were 2, 2.25, 2.5, and 3 feet wide; the flukes for soil V were 1.5 and 1.75 feet wide. Both L/B = 1.5 and 2 were chosen for all soils. Smaller flukes (L/B = 1) were generally not chosen because experience indicates that their penetration to the required deeper depths is difficult.

4. Evaluate Penetrability of Chosen Flukes. The penetrability of the most promising flukes was evaluated using the technique described by True (Smith, 1971) slightly modified to agree with the results reported by Christians, 1967. Typical results are presented in Figure A-3 for the soft clayey silt soil, type IV. These data shown that the curves for each L/B are practically superimposed for the fluke sizes considered. This trend followed for the other soil types.

5. Choose Fluke(s). Table A-1 summarizes the fluke velocity and energy requirements needed to satisfy the goal of 30 kips short-term (20 kips long-term) holding capacity. Penetration velocities for 30 kips were determined from the appropriate embedment depth-penetration velocity curve, such as in Figure A-3. Embedment depths used to enter the curves are derived from the appropriate fluke width-embedment depth curves, such as in Figure A-2. Based upon velocity and energy requirements, a different fluke is needed for each soil for optimization; this however, is impractical. Two flukes were chosen to satisfy all seafloor sediments; a 1.5 x 3-foot fluke for soils like Types I, II, III, and V and a 2.5 x 5-ffot fluke for soft seafloor sediments, like soil IV. Preliminary estimates indicate that the larger fluke will satisfy clay soils with $c/\bar{p}$ ratios ranging from 0.15 to 1, and the small fluke will satisfy clay soils with $c/\bar{p}$ ratios greater than 0.6. This overlap will in some cases allow the flukes to be tailored to specific situations.

The smaller fluke, defined as the sand fluke, provides an acceptable compromise for the more competent seafloors. It is small enough to function in dense sand, and large enough to function in a non-plastic silt. This fluke should equal or exceed design specifications in all soils but soft clay. The deeper penetrations of the smaller fluke are more desirable to minimize the effects of scour and to ensure "deep" anchor behavior. The small size also simplifies handling and stowage. A 2.5 x 5-foot fluke, defined as the clay fluke, seems to be the best choice for soft clay. The required velocity and energy can be realistically attained, and the fluke is still reasonably sized. These decisions were not strictly accomplished by analyzing Table A-1. This table helped eliminate many flukes due to excessive requirements, while evaluation of curves of holding capacity versus penetration velocity (see Figure A-4 for typical curves) resolved the decision. These curves were developed by synthesizing data from holding capacity-embedment

depth curves and from penetration velocity-embedment depth curves after adjusting embedment depth by fluke keying distance. When two flukes yielded about the same results, the narrower fluke was always chosen because its penetration would be less affected by the presence of layering formed through either normal deposition or turbidity currents.

Figure A-5 summarized the anticipated performance of the sand (1.5 x 3-foot) and clay (2.5 x 5-foot) flukes. The minimum fluke velocities required of the gun system were 200 fps and 183 fps for the sand and clay flukes, respectively. To account for uncertainties involved in the theories used as bases for this analytical study, minimum velocities were set as 275 fps and 225 fps for the sand and clay flukes, respectively. According to Figure A-5, these velocities will result in the following tabulated short-term holding capacities.

Soil	Short-Term Holding Capacity (kips)
I. Silt	40
II. Silty sand	47
III. Dense sand	>60
IV. Clayey silt	35
V. Carbonate bonded silty clay	53

Table A-I. Fluke Energy and Velocity Requirements

Soil Type	Fluke Length/ Fluke Width, L/B	Anchor Depth After Keying (ft)	Fluke Width, B (ft)	Penetration Velocity for 30 Kips Holding Capacity (fps)	Kinetic Energy (ft-kips)
I. Medium Density Sandy Silt	1.5	23	1.5	270	318
		16.5	1.75	192	181
		12.5	2.0	150	122
	2.0	18	1.5	200	188
		13	1.75	155	126
		10	2.0	130	100
II. Medium Density Silty Sand	1.5	16	1.5	237	242
		12	1.75	175	150
		9.5	2.0	142	108
	2.0	12.5	1.5	177	149
		9.5	1.75	150	120
		8.8	2.0	148	132
III. Dense Sand	1.5	8	1.5	167	120
		7.5	1.75	170	142
		7.0	2.0	170	157
	2.0	7.0	1.5	156	115
		6.7	1.75	167	145
		6.4	2.0	175	170
IV. Deep Water Clayey Silt	1.5	48	2.0	440	1050
		39	2.25	300	554
		30	2.5	210	320
		21	3.0	150	218
	2.0	37	2.0	345	703
		30	2.25	250	420
		23	2.5	183	254
		16	3.0	128	157
V. Carbonate Bonded Silty Clay	1.5	12	1.5	147	100
		8	1.75	110	64
	2.0	8	1.5	112	61
		7.5	1.75	115	72

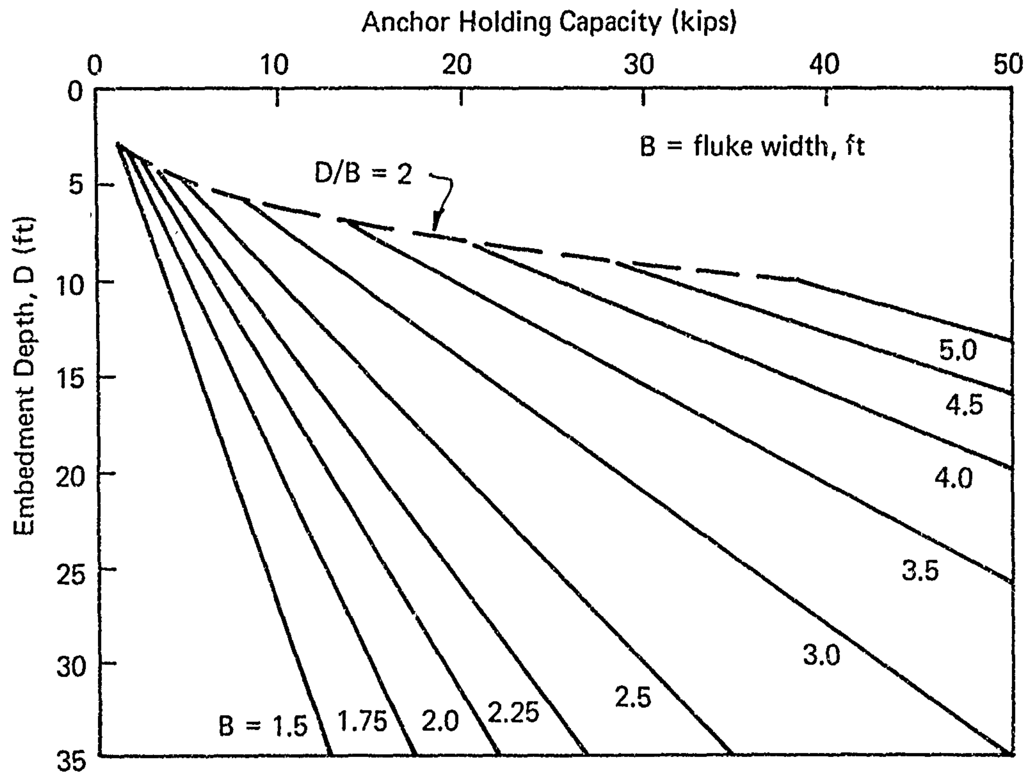

Figure A-1. Anchor holding capacity versus embedment depth for Soil IV at L/B = 1.5.

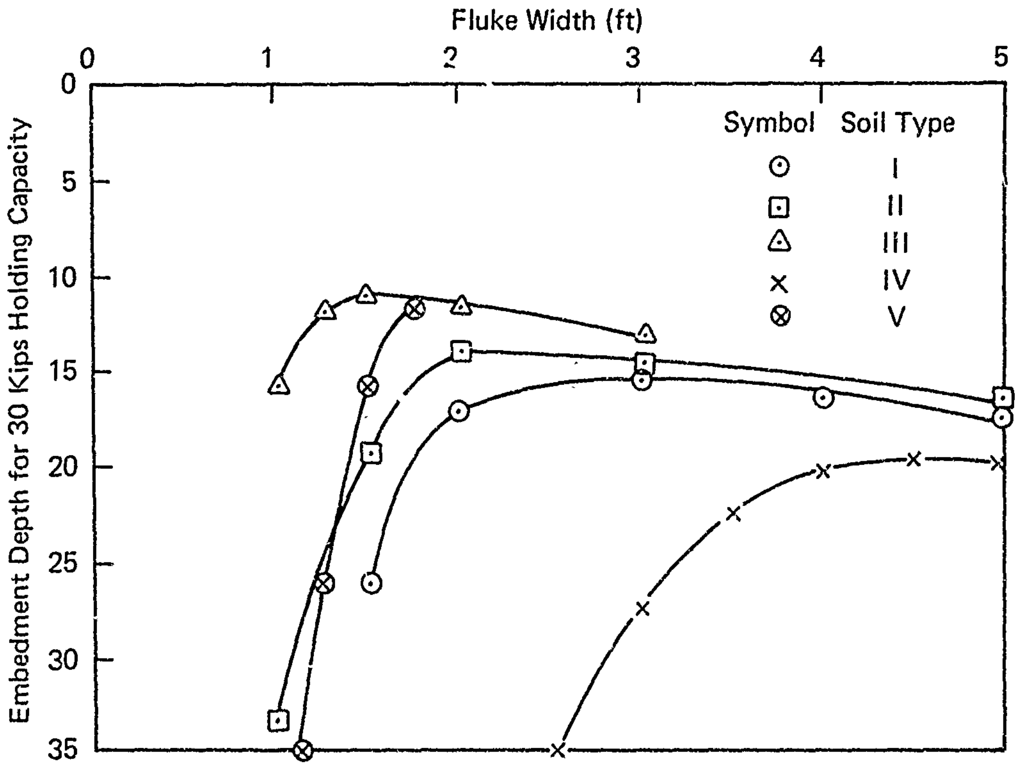

Figure A-2. Fluke width versus embedment depth before keying for 30 kips holding capacity; L/B = 1.5.

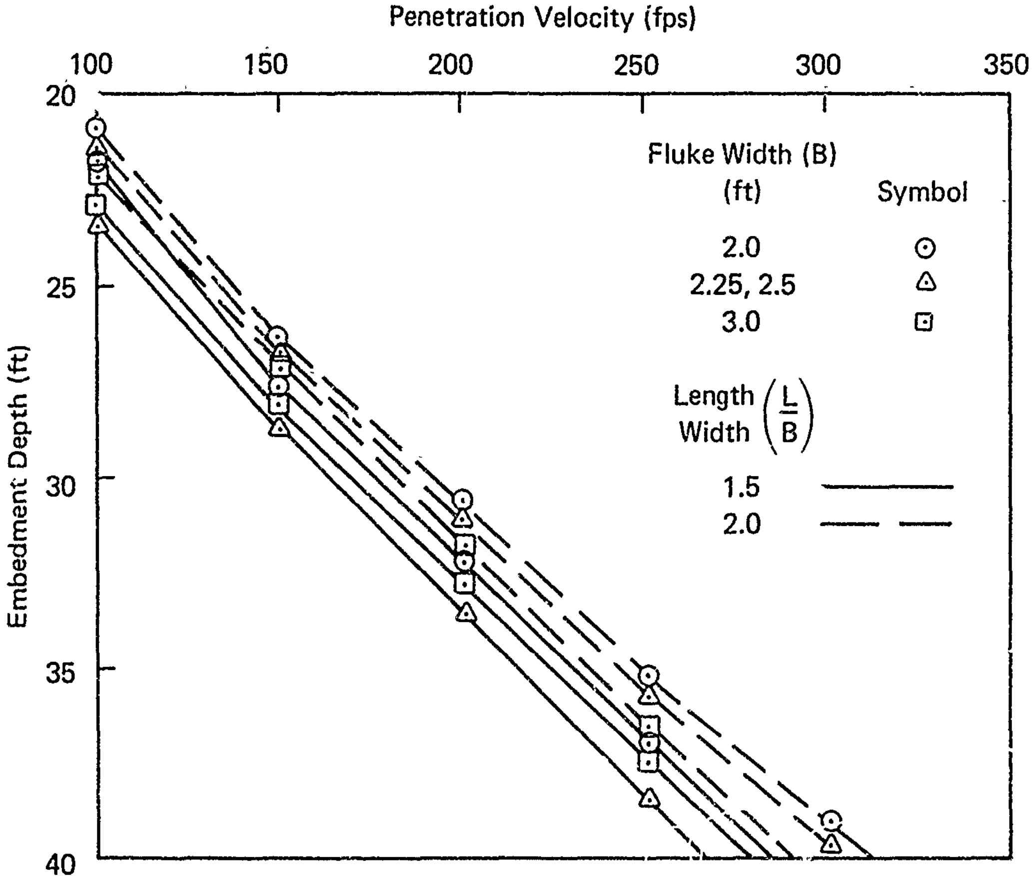

Figure A-3. Penetration velocity versus embedment depth before keying for Soil IV.

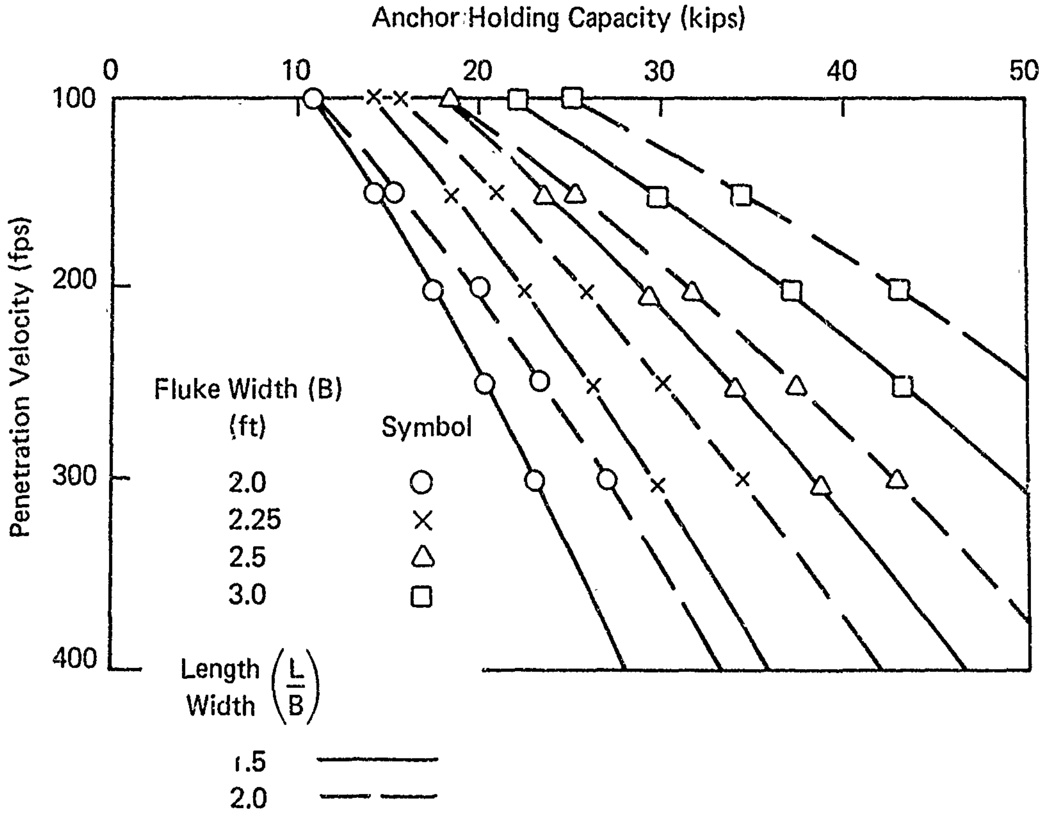

Figure A-4. Anchor holding capacity versus penetration velocity for Soil IV.

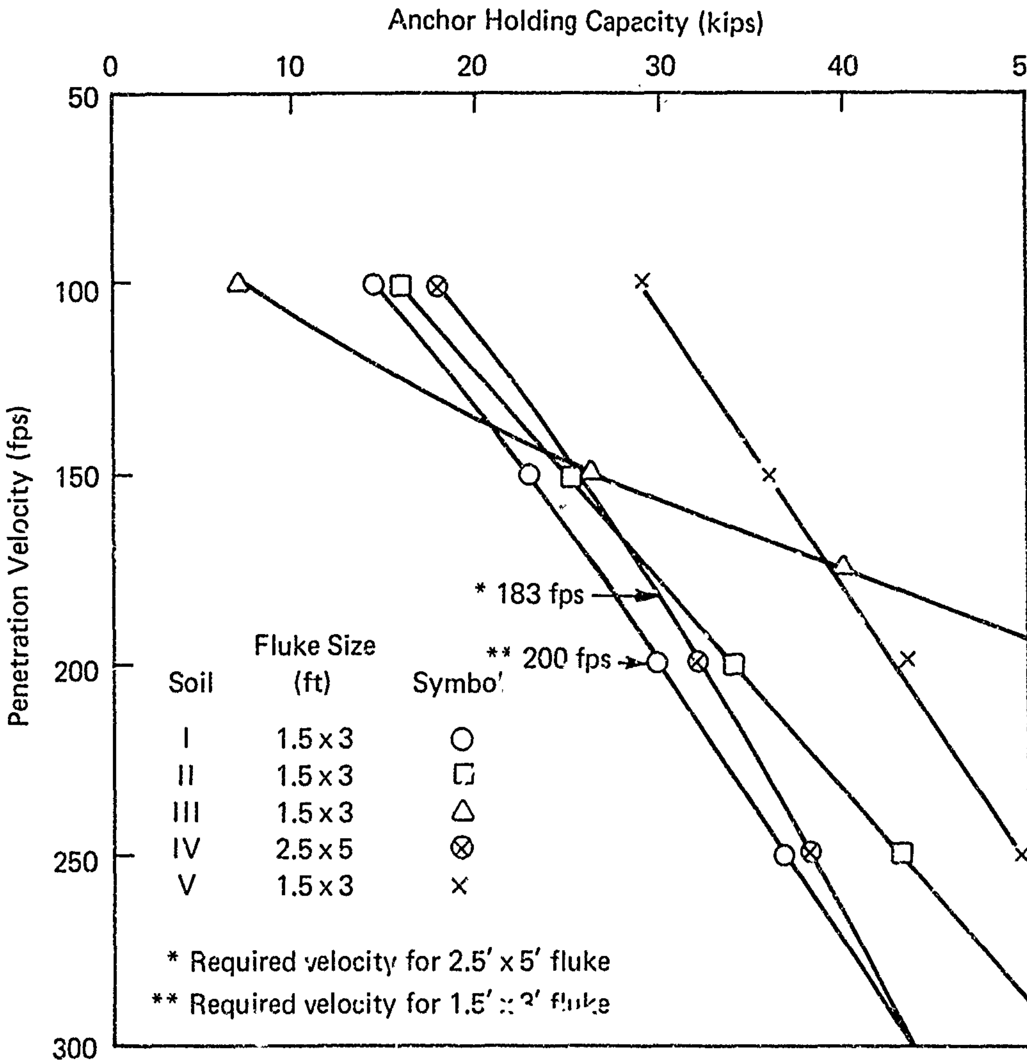

Figure A-5. Anchor holding capacity versus penetration velocity for the deep water anchor flukes.

Appendix B
OPTIMIZATION OF PROPELLANT CHARGE

The Naval Ordnance Station (NOS) at Indian Head, Maryland provided NCEL with a launcher system design, propellant selection, and a basic range of propellant charge weights to satisfy a broad range of specifications supplied by NCEL. These specifications included an estimate of the water depths at which the anchor was to operate, a maximum gun barrel length, estimates of two projectile weights, required velocities for these projectiles, and a maximum tolerable acceleration. NOS selected a shortened 90mm Army gun tube for the launcher system. Using a maximum operating pressure of 35,000 psi the required projectile stroke to achieve design velocities was 26 inches. Eleven inches were required for a cartridge to house the propellant charges; therefore, the 90mm gun tube length was set at 37 inches. Through analysis of ballistic performance with different types of propellants using the data supplied by NCEL and the 90 mm gun tube, NOS determined that standard Navy pyrotechnic propellant was best at providing acceptable projectile velocities over the range of operable water depths. With the propellant type and characteristics of the gun tube known, NCEL could determine the propellant charge weights needed to optimize performance of the chosen anchor projectiles.

Defined parameters were now:

Operable water depths:	100 feet to 20,000 feet
Gun barrel:	37 inches long; 26-inch projectile stroke; 11-inch cartridge
Shot start pressure:	3,000 psi
Propellant:	Navy pyrotechnic
Projectile weights:	300 pounds and 490 pounds
Launch vehicle weight:	1540 pounds
Projectile muzzle velocities goals:	225 fps, 490-pound projectile 275 fps, 300-pound projectile
Maximum allowable gun barrel pressure:	35,000 psi

With this information an optimization study to select the best combination of charge weight and web thickness (material thickness between perforations in propellant) was performed. The goal was to achieve a balance between performance in shallow and deep water for both projectiles using a single web thickness and a minimum of different charge weights. A computer program developed by NOS was used extensively in this optimization. Charge weights ranging from 2.25 to 3.75 pounds in .25-pound increments and web thickness from .06 to .11 inches in .01-inch increments were examined for both projectiles over the entire depth range. Plots were made of projectile velocity versus water depth for each web thickness.

On each plot, curves representing performance with different charge weights for each projectile were drawn. In addition, a curve representing the limiting gun barrel pressure relative to the water pressure (35,000 psi) was drawn for each projectile. An example of such a plot is shown in Figure B-1.

The ideal situation would have been to find a single web thickness and a single charge weight that would give acceptable performance over the depth range of interest for both projectiles. Such was not the case. Examination of the performance curves indicated that at least three separate charge weights would be required to approach uniform performance with depth. The scheme to select charge weights for a given web thickness was to find the charge weight that gave a 35,000 psi gun barrel pressure at a water depth of 20,000 feet with the 490-pound projectile. A second charge weight was then found such that at some depth (usually around 10,000 feet) a shift to this second charge weight would again give a 35,000 psi gun barrel pressure. This second charge would be used from the shift-depth to the minimum operating water depth. This second charge was then used with the 300-pound projectile at 20,000 feet so long as the gun barrel pressure would not exceed 35,000 psi; if so, the second charge weight was adjusted down. The same performance balancing procedure used with the 490-pound projectile was then applied to the 300-pound projectile. Another shift-depth was found and a third charge weight selected. The result of this process was that one charge weight, the second, was common to both projectiles.

It was determined that the .07-, .08-, and .09-inch web sizes could satisfy the requirements. The .06-inch web could not give acceptable velocities to the 490-pound projectile, gun barrel pressure being the limiting factor. The .10-inch web was not suitable, as performance with the 300-pound projectile started to fall off rapidly, the limiting factor being the amount of propellant that could be loaded. In selecting between .07-, .08-, and .09-inch web thickness it was noted that thicker web increased the performance of the 490-pound projectile but decreased the performance of the 300-pound projectile, and the thinner web produced the reverse effect. It appeared that the .08-inch web was the best for all-around performance with the two projectiles. For the 300-pound projectile a 3.5-pound charge is used down to 10,000 feet and a 2.95-pound charge in water depths between 10,000 and 20,000 feet. For the 490-pound projectile the 2.95-pound charge is used to a water depth of 10,000 feet and a 2.6-pound charge is used between 10,000 feet and 20,000 feet. Figure B-2 shows the charge weight and resulting performance. Minimum performance for the 300-pound projectile is about 325 feet per second, and minimum performance of the 490-pound projectile is about 245 feet per second. Both of these values exceed the established goals of 275 and 225 feet per second, respectively.

An important factor in designing particular installations with the deep water anchor is that performance can be optimized to higher velocities as required. The performance of the 300-pound projectile can be up-graded to about 400 feet per second at water depths to several

thousand feet. The velocity of the larger projectile can also be upgraded to about 300 feet per second, also at water depths to a few thousand feet. This will be done for at-sea testing. During the at-sea test program, propellant with a .074-inch web will be used, the same size as used during the on-land test program. This size web is being used because it is available from stock on-hand and is very near to the chosen web size.

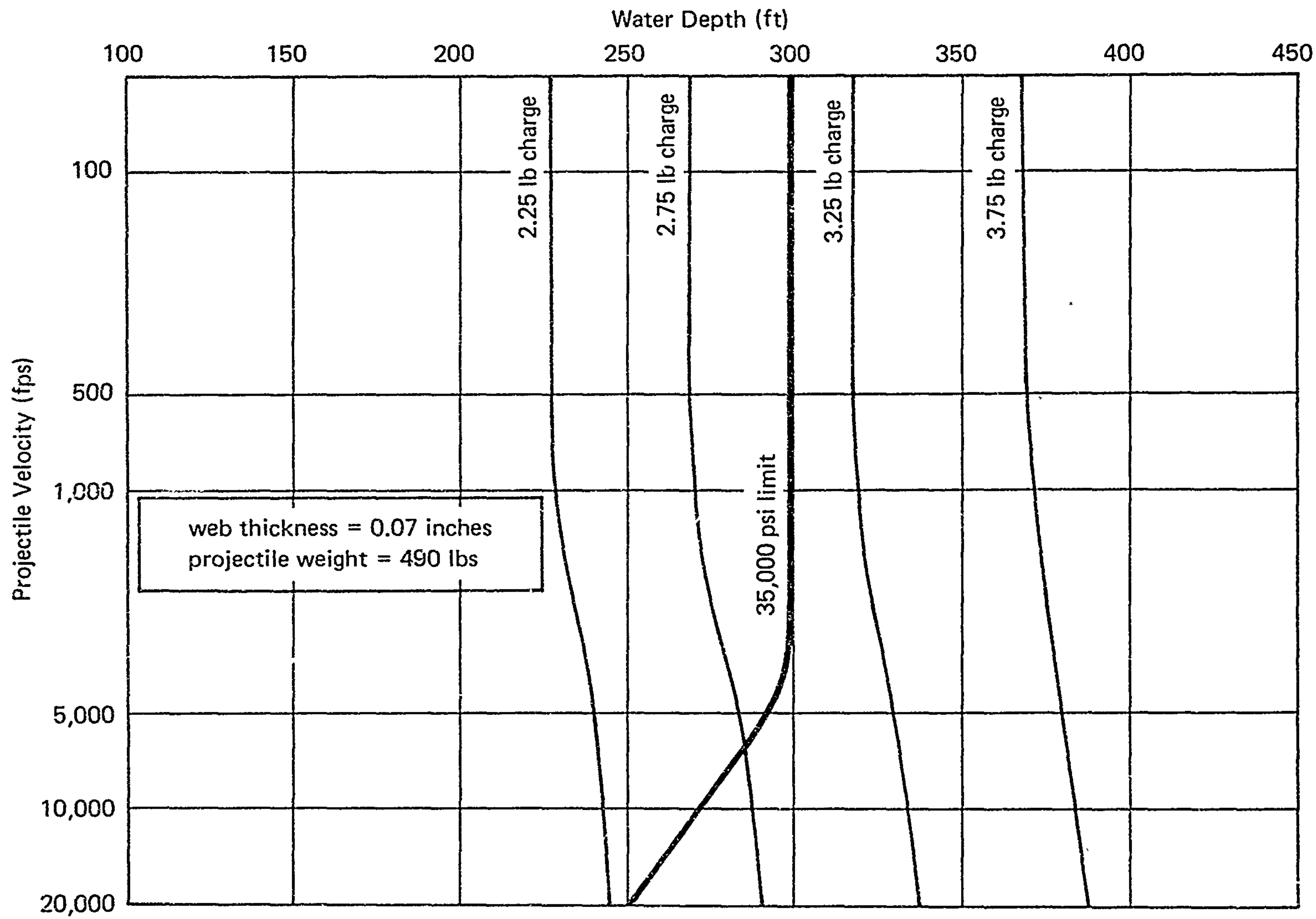

Figure B-1. Projectile velocity versus water depth at different charge weights with a .07-inch web thickness and a 490-pound projectile.

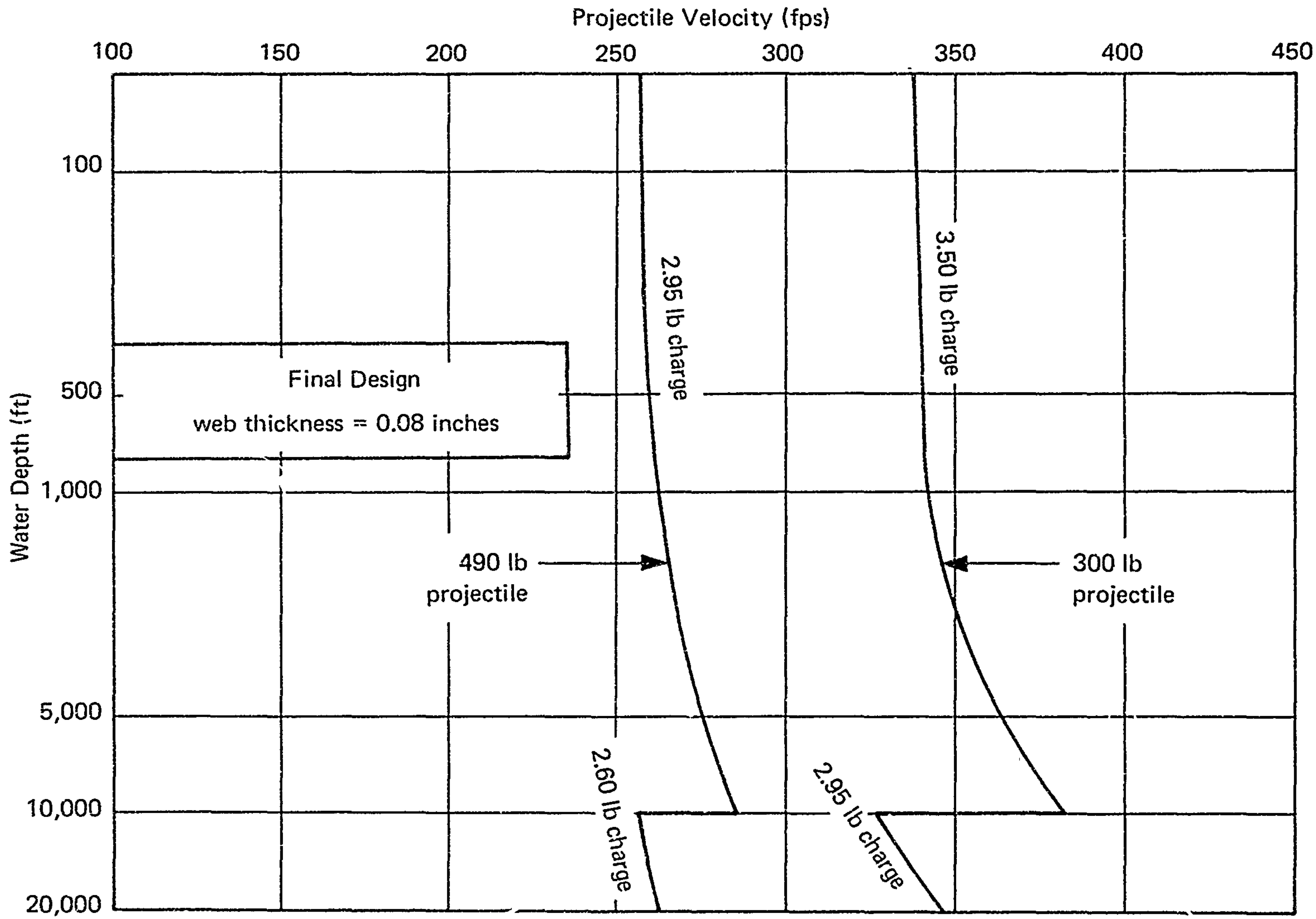

Figure B-2. Final design: propellant weights and web thickness for anchor flukes.

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NOMENCLATURE

B	fluke width
D	depth of embedment
L	fluke length
c	undrained shear strength
$\bar{p}$	effective overburden pressure
γ_b	buoyant unit weight of soil
ϕ	soil angle of internal friction